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General Purpose Technologies and Productivity Surges:

Historical Reflections on the Future of the ICT Revolution

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General Purpose Technologies and Surges in Productivity: Historical Reflections on the Future of the ICT Revolution

In this essay we reflect on the relevance of early twentieth century American experience for understanding the more general phenomenon of recurring prolonged swings in the TFP growth rate in advanced industrial economies. After a "productivity pause" of some three decades, during which gross manufacturing output in the US grew at less than one percent per annum relative to inputs of capital and labor, TFP in this sector expanded at more than five percent per annum between 1919 and 1929. This remarkable discontinuity has largely been overlooked by modern productivity analysts and economic historians alike; yet it contributed substantially to the absolute and relative rise of the US domestic economy's TFP residual, and in many respects may be seen as the opening of the high-growth era that persisted into the 1970s.[1]

The shift in the underlying technological regime that is implied by this statistically documented discontinuity can be traced to critical engineering and organizational advances connected with the electrification of industry. These developments marked the culminating phase in the diffusion of "the dynamo" as a general purpose technology (GPT) that made possible significant fixed-capital savings, while simultaneously increasing labor productivity. Yet, a narrow technological explanation of the post-World War I industrial productivity surge proves to be

[1] This paper builds upon the detailed re-examination of manufacturing productivity in David and Wright, "Early Twentieth Century Growth Dynamics." We are grateful to Sir John Habakkuk, Angus Maddison, and R.C.O. Matthews for their comments and suggestions on a previous draft.

inadequate. It neglects the concurrence of those developments with important structural changes in US labor markets, and fails to do justice to the significance of complementarities that emerged between managerial and organizational innovations and the new dynamo-based factory technology, on the one hand, and, on the other, between both forms of innovation and the macroeconomic conditions of the 1920s.

We explore the latter, more complex formulation of the dynamics of GPT diffusion by considering the generic and the differentiating aspects of the US experience with industrial electrification in comparison with that of the UK and Japan. The cross-national perspective brings to light some differences between leader and follower economies in the dynamics of GPT diffusion, and its relationship to the strength of surges in productivity growth. Our Anglo-American comparison serves also to underscore the important role of the institutional and policy context with respect to the potential for upgrading the quality of the workforce in the immediately affected branches of industry.

The concluding sections of the essay offer some reflections on the analogies and contrasts between the historical case of a socio-economic regime transition involving the electric dynamo and the modern experience of the information and communications technology (ICT) revolution. Contextualizing the GPT concept in explicitly historical terms sheds light on the paradoxical phenomenon of the late twentieth century productivity slowdown, and also points to some contemporary portents of a future phase of more rapid ICT-based growth in total factor productivity.

A Brief Recapitulation

In his introduction to John Kendrick's study of productivity trends in the United States, Solomon Fabricant noted:

> A distinct change in trend appeared some time after World War I. By each of our measures, productivity rose, on the average, more rapidly after World War I than before...The change in trend...is one of the most interesting facts before us. There is little question about it. It is visible not only in the indexes that Kendrick has compiled for the private domestic economy...It can be found also in his figures for the whole economy, including government, as well as in his estimates for the groups of industries for which individual productivity indexes are available.[2]

The historical break was heavily though not exclusively concentrated in the manufacturing sector. Kendrick's estimates put the decadal growth of TFP at approximately 22 percent for the whole of the private domestic economy, while the corresponding figure for manufacturing was 76 percent, and for mining 41 percent. TFP growth in transportation, communications and public utilities exceeded the private domestic average by lesser amounts, while the farm sector was in last position with a relatively low gain of 14 percent. At the heart of the story was manufacturing, where the discontinuity was particularly marked (Figure 1).[3]

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[2] Kendrick, *Productivity Trends*, p. xliii.

[3] The discontinuity in decadal measures was not an artifact of cyclical fluctuations accentuated by wartime and postwar demand conditions. Although we do not have annual TFP data, logarithmic regressions using data on labor productivity show that trend growth jumped from 1.5 percentage

Having pinpointed manufacturing, we may ask whether the productivity surge of the 1920s was broadly based within that sector, reflecting common forces at work in the economy; or whether instead it was concentrated in a small number of rapidly changing industries. The distinction may be illustrated with the terms deployed by Arnold Harberger in his 1998 Presidential address to the American Economic Association: “yeast”-like processes expand uniformly under a common fermenting agency; whereas “mushroom-like” innovations reflecting “real cost reductions stemming from 1001 different causes,” and being highly localized and idiosyncratic to particular industries and even to individual firms, tend to pop up at random places in the field of industry. Although Professor Harberger finds that the “mushroom” metaphor better describes the distribution of TFP growth among industries in the late twentieth century (slow productivity-growth) US economy, we find, in contrast, that the 1920s was a decade of yeast-like manufacturing productivity advances.

When the branches of US manufacturing are aggregated into standard industrial groups, it appears that 13 of the 14 major categories experienced an *acceleration* in the growth of multifactor productivity between 1909 and 1919, and 1919 and 1929.[4] When

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points per annum during 1899 to1914, to 5.1 during 1919 to 1929. See David and Wright, “Early Twentieth Century Growth Dynamics,” Figure P3.

[4] The lone exception, Transportation Equipment, was deviant only because of its exceptional productivity growth during the previous decade, not because it was below average for the 1920s. These findings, previously reported by David in “Computer and Dynamo,” (and presented also in David and Wright, “Early Twentieth Century Growth”) account for purchased energy inputs in the multi-factor productivity measurement. This is appropriate, especially in view of the substitution of

the categories are further disaggregated, to identify the fastest-growing individual industries in terms of real net output per manhour, we find that the high-fliers were broadly dispersed among nine larger industry groups; six of these aggregates boasted two or more high-growth members. The flat Lorenz-like diagram displayed in Figure 2 (developed using Harberger's method) makes immediately apparent the contrast between the 1920s and the "pro-mushroom" findings of the 1970s and 1980s. Evidently the post-1919 industrial productivity surge reflected broad, generic developments that were impinging widely upon US manufacturing activities.

What sorts of forces were sufficiently pervasive and potent as to have these far-reaching effects? We highlight two: first, the culmination of the dynamo revolution that had been underway as a technological trajectory since the nineteenth century, but which did not realize its engineering potential for major productivity gains until the 1920s; and second, the restructuring of US manufacturing labor markets, in the wake of the closing of mass European immigration after 1914. Each of these developments had its own prior history; but the productivity surge reflected the confluence of these two largely independent streams of development.

As recounted by David in “Computer and Dynamo,” the transformation of industrial processes by electric power technology was a long-delayed and far from automatic business. It did not acquire real momentum until after 1914 to 1917, when the rates charged consumers by state-regulated regional utilities fell substantially in real terms, and central station generating capacity came to predominate over generating capacity in isolated industrial plants. Rapid efficiency gains in electricity generation

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purchased electricity for the services of on-site capital equipment in the form of prime movers, which was taking place during the era in question.

during 1910 to 1920 derived from major direct investments in large central power plants, but also from the scale economies realized through integration and extension of power transmission over expanded territories. These developments were not simply matters of technology, but also reflected political and institutional changes that allowed utilities largely to escape regulation by municipal and town governments, facilitating the flow of investment capital into holding companies presiding over centrally managed regional networks. Together these supply-side changes propelled the final phase of the shift to electricity as a power source in US manufacturing, from just over 50 percent in 1919 to nearly 80 percent in 1929.[5]

But the protracted delay in electrification was not exclusively due to problems on the supply side of the market for purchased electrical power. The slow pace of adoption prior to the 1920s was attributable largely to the unprofitability of replacing still serviceable manufacturing plants adapted to the old regime of mechanical power derived from water and steam. Coexistence of older and newer forms of capital often restricted the scope for exploiting electricity’s potential. Prior to the 1920s, the “group drive” system of within-plant power transmission remained in vogue. With this system — in which electric motors turned separate shafting sections, so that each motor drove related groups of machines — primary electric motors often were merely added to the existing stock of equipment.[6] When the favorable investment climate of the 1920s opened up the potential for new, fully electrified plants, firms had the opportunity to switch from group drive to “unit drive” transmission, where individual electric motors were used to run

[5] David and Wright, “Early Twentieth Century Growth Dynamics,” Figure E1, derived from DuBoff, *Electric Power*.

[6] See Devine, “From Shafts to Wires”; Devine, “Electrified Mechanical Drive”.

machines and tools of all sizes. The advantages of the unit drive extended well beyond savings in fuel and in energy efficiency. They also made possible single-story, linear factory layouts, within which reconfiguration of machine placement permitted a flow of materials through the plant that was both more rapid and more reliable. According to the surveys of American manufacturing directed by Harry Jerome, rearrangement of the factory contributed to widespread cost savings in materials handling operations, serializing machines and thereby reducing or eliminating "back-tracking".[7]

The package of electricity-based industrial process innovations just described could well serve as a textbook illustration of *capital-saving* technological change. Electrification saved fixed capital by eliminating heavy shafts and belting, a change that also allowed factory buildings themselves to be more lightly constructed, because they were more likely to be single-story structures whose walls no longer had to be braced to support the overhead transmission apparatus. The faster pace of material throughput amounted to an increase in the effective utilization of the capital stock. Further, the frequency of downtime was reduced by the modularity of the unit drive system and the flexibility of wiring; the entire plant no longer had to be shut down in order to make changes in one department or section of the factory.[8] Notice too that Henry Ford's transfer-line technique and the speed-up of work that it permitted was a contributory element of the high throughput manufacturing regime, as were the new continuous process technologies that grew in importance during this era.

These effects are confirmed by the sharp fall in the capital-output ratio during the 1920s, reversing the long-term trend. As with TFP growth, the pattern was pervasive:

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[7] Jerome, *Mechanization in Industry*, pp. 190-91.

[8] Schurr et al, *Electricity in the American Economy*, esp. pp. 29-30 and 292-93

All but two of the seventeen major industry groups show a fall during this decade, whereas the ratio had been rising in every one of these groups during 1899 to 1909, and in twelve of seventeen during 1909 to 1919. A scatter plot demonstrates that this increase in capital productivity was directly associated with the electrification of primary horsepower, a correlation that strengthened across the 1920s (Figure 3).

A proper historical account of the 1920s productivity revolution, however, cannot be confined to the cluster of manufacturing techniques that were diffusing into use in that decade. Equal notice must be taken of a second broad force operating on the US economy at that time, namely the sharp increase in the relative price of labor. Relative to the general price level, the hourly wage of industrial labor was 50 to 70 percent higher after 1920 than it had been a decade before (Figure 4). This change was most immediately associated with the end of mass European immigration, which had averaged more than one million per year during the decade prior to 1914, but was blocked during the war and then decisively closed by legislation in 1920 and 1924. The rise in real wages ushered in a sweeping change in the functioning of labor markets, reflected in a fall in turnover and an upgrading of hiring standards. As we interpret these events, reinforcing changes on both sides of the labor market generated a "regime transition," towards a new set of relationships that we may call the High Wage Economy.

Although this history was largely independent of electric power technology, it was the confluence of these two streams that gave the decade of the 1920s its truly extraordinary character. Both were facilitated by favorable macroeconomic conditions, including the high rate of investment in new plant and equipment; the new flexibility in plant location and design facilitated the reorganization of job assignments and labor systems as well as physical arrangements. Indeed, we would go further, suggesting that there were positive micro-level interactions between electrification and rising labor productivity. Another scatter diagram, relating the growth of capital and labor productivity across the array of industries during the decade, shows that there was a *positive* correlation between the two -- not the negative association that one would expect using a simple factor substitution model (Figure 5). We argue that the technological and organizational changes just reviewed also exerted a positive influence on the efficiency of labor inputs, through at least three channels: (a) an increase in the effective utilization of labor capacity, by improving the speed and reliability of materials transmission; (b) a higher premium on mature, reliable, longer-term employees, because of the vulnerability of electrified plant systems to disruption; (c) increased scope for individual specialization and the exercise of discretion, made possible by the localization of power supply under the unit drive system.

Generalizing the Dynamo: Generic Features of General Purpose Technologies

The diffusion of the dynamo has served as something of a paradigmatic example for economists working in the spirit of the new growth theory who have sought to generalize the idea of "general purpose technologies" with applications in diverse sectors of the economy. As formulated by Bresnahan and Trajtenberg:

> Most GPTs play the role of "enabling technologies," opening up new opportunities rather than offering complete, final solutions. For example, the productivity gains associated with the introduction of electric motors in manufacturing were not limited to a reduction in energy costs. The new energy sources fostered the more efficient design of factories, taking advantage of the

newfound flexibility of electric power. Similarly, the users of micro-electronics benefit from the surging power of silicon by wrapping around the integrated circuits their own technical advances. This phenomenon involves what we call Innovational complementarities (IC), that is, the productivity of R&D in a downstream sector increases as a consequence of innovation in the GPT technology. These complementarities magnify the effects of innovation in the GPT, and help propagate them throughout the economy.[9]

The interest in generalization has in turn stimulated efforts to consolidate our understanding of the defining features of GPTs, and to extend the list of historical examples. According to the most carefully developed criteria proposed by Lipsey, Bekar, and Carlaw, GPTs are technologies that share four characteristics:

(1) Wide scope for improvement and elaboration;

(2) Applicability across a broad range of uses;

(3) Potential for use in a wide variety of products and processes;

(4) Strong complementarities with existing or potential new technologies.[10]

Using these criteria, Lipsey and his co-authors identify an extensive list of historical and contemporary GPTs, from power delivery systems (waterwheel, steam, electricity, internal combustion) and transport innovations (railways and motor vehicles) to lasers and the internet. They also extend the concept to such organizational technologies as the factory system, mass production, and flexible manufacturing. In the same volume, Nathan Rosenberg extends the application still further into the

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[9] Bresnahan and Trajtenberg, "General Purpose Technologies," p. 84.

[10] In Helpman (ed.), *General Purpose Technologies*, pp. 38-43.

institutional structure of knowledge itself, arguing that the rise of Chemical Engineering in the US may be usefully viewed as a GPT.[11]

One has only to consider the length of such proposed lists of GPTs to begin to worry that the concept may be getting out of hand. History may not have been long enough to contain this many separate and distinct revolutionary changes. On closer inspection, it may be that some of these sweeping innovations should be better viewed as sub-categories of deeper conceptual breakthroughs in a hierarchical structure. Alternatively, particular historical episodes may be fruitfully understood in terms of interactions between one or more GPTs on previously separate historical paths. Quite clearly, an important aspect of the dynamo revolution was the technological confluence, or convergence, of electrification with other trajectories of industrial innovation, each of which might be considered a species of GPT. Three among these are especially notable in the present connection:

(a) the fixed transfer-line layout of assembly operations that came into full fruition in the Ford Highland Park plant on the eve of World War I diffused rapidly and widely during the 1920s, because, as Hounshell points out, Ford was deliberately open in promoting the logic and engineering specifics of this system of mass production by means of interchangeable parts. Electric power transmission by wire, rather than by drive-shafts was better suited to this new manufacturing regime (as one can see from the use made of group and unit drives at Highland Park itself.)[12]

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[11] *Ibid.*, pp. 167-192.

[12] Hounshell, *American System to Mass Production*, pp.

(b) automated materials handling was a generic labor-saving development that featured prominently among the new innovations of manufacturing mechanization reported in Jerome's survey; these too did not require electrification, although in some cases such as the use of battery powered fork-lifts, the availability of cheap purchased power for recharging was important.

(c) continuous process chemical technologies, which as Rosenberg emphasizes implemented the unit system principles of A.D. Little, made extensive use of electro-mechanical and electro-chemical relays for control, and many of these processes were heat-using, and so were dependent upon purchased electricity for large-scale operations.

For the sake of brevity and the thematic unity provided by considering the dynamics of the diffusion of a broad GPT, however, we prefer to regard the foregoing streams of technical development as subsidiary, or perhaps "tributary." Hence, we focus our discussion on the productivity impact of electric power technology and its applications, regarding the dynamo technology as a GPT of a higher order, and more pervasive and transformative agent than the others.

But we do see the explosive productivity growth of the 1920s as the result of a confluence between the dynamo GPT and the clustering of electricity-based- or -enhanced manufacturing process technologies, on the one side, and the emergence of a new organizational regime that created what might be called that High Wage Path for the mid-twentieth century US economy. This development was triggered by a particular conjunction of macroeconomic and labor market conditions, and insofar as it became institutionalized in the practices and expectations upon which the strategies of major US industrial corporations were premised, it might itself have a certain claim to be regarded as a GPT. But we prefer not to burden formulations of the GPT concept with this degree of historical specificity. But we hold to the view that appropriate *applications* of the concept should be explicitly historical in the sense that the impact of a new technology is typically conditioned by just such conjunctions in timing.

Inevitably, some of the sense of historical context is lost in the more abstract theoretical treatments. In the recent collection of essays edited by Helpman, GPTs are variously characterized in terms of inter-industry linkages, R&D investments, scale economies, coordination problems, spillover, and other structural features, often applied to perfect-foresight, general-equilibrium models that seem to deny the premise of historical technological trajectories. But this may be a necessary phase in the early diffusion of a concept within the discipline of economics. And it is noteworthy that even in models that are stripped-down and simplified, GPT phenomena readily generate alternating phases of slow and rapid productivity growth, and corresponding phases of slowed or accelerated real wage growth. Depending on the formulation, the "output slowdown" phase may be attributed to the diversion of resources into knowledge investment during the gestation phase; to increased rates of obsolescence in the older capital stock and in labor force skills; to measurement problems with respect to both the capital stock and to new goods and services; to the need for industry-specific adaptations, which have to wait upon progress in the GPT itself; or to risks and uncertainties facing adopters, which decline only with improvements and cost reductions by suppliers.[13]

Virtually all of these aspects of discontinuity may be observed in our historical case of American electrification. We would add to this list, however, the need for

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[13] See, particularly, the essays by Helpman and Trajtenberg, and by Aghion and Howitt, in Helpman, *General Purpose Technologies*.

organizational and above all for *conceptual* changes in the ways tasks and products are defined and structured. And because major technological revolutions can be expected to have social and distributional consequences, political adjustments may also be required, if the full potential of the new technology is to be realized. Changes of this sort are intrinsically subject to delay and discontinuity. As noted above, the historical US episode saw such transformations in immigration policy, in education, and in the recruitment and retention policies of industrial employers.

Was this Phenomenon Uniquely American? Evidence from Comparative Electrification

Was the experience of delayed and then accelerated TFP growth, associated with electrification, uniquely an American phenomenon, or do we find similar patterns elsewhere?[14] A truly global analysis would be a vast project, but an appropriate place to begin is with the United Kingdom. Of course, there were so many contrasts in economic conditions between these two countries during the period of interest, that there is no assurance that any simple comparisons would be at all meaningful. As a self-sufficient continental power, the US escaped damage during World War I and was largely insulated from the travails of the international economy during the 1920s; Britain, on the other hand, was afflicted during that decade by the loss of traditional markets for manufactured goods and the overvaluation of the pound.

[14] Special thanks are due at this point to Angus Maddison and R.C.O. Matthews for their privately communicated comments on David and Wright,"Early Twentieth Century Growth Dynamics," in which both suggested that we take notice of the experiences of industrial nations other than the US.

In view of these differences, it comes as something of a surprise to find a remarkable number of qualitatively similar patterns in the British productivity data. These emerge when the record for the period 1924 to 1937, is contrasted with that for the pre-war era. Matthews, Feinstein, and Odling-Smee report that TFP for the economy as a whole rose at 0.70 percent per year during 1924 to 1937, compared to 0.45 percent per year for 1873 to 1913, the acceleration being led by manufacturing, where TFP growth jumped from 0.6 percent to 1.9 percent per year.[15] A particularly striking feature of this surge was that the capital-output ratio in manufacturing declined at the rate of 2.4 percent per annum during 1924 to 1937, reversing the trend of the entire period stretching from 1856 to 1913.[16] Not only did the productivity of manufacturing capital increase for the sector as a whole, but the authors go on to note:

> It is remarkable that a fall in the capital-output ratio between 1924 and 1937 is found in every manufacturing group without exception, including rapidly growing industries such as vehicles and electrical engineering, where a legacy of old excess capacity can hardly have been important.[17]

Inspection of cross-section relationships within manufacturing suggests that, as in the US, there was a positive correlation between the growth of capital productivity and of labor productivity during this period.[18]

When we turn to the text of Matthews, Feinstein and Olding-Smee for an explanation of these patterns, we find that at the top of the list is electrification, “a

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[15] Matthews, Feinstein and Odling-Smee, *British Economic Growth*, p. 229.

[16] *Ibid.*, p. 378.

[17] *Ibid.,* p. 384.

[18] *Ibid.,* p. 240.

change that extended over the whole range of manufacturing...a development that was accompanied by an increase in the proportion of electricity purchased as opposed to generated within the firm." The authors note that

> apart from this straightforward capital-saving effect (as far as manufacturing was concerned), it is likely that a capital-saving effect also resulted because electrification permitted the more flexible and efficient use of any given horsepower. One of these consequences was the extension of the use of (relatively cheap) machine tools.[19]

More recently, Feinstein, Temin and Toniolo identify electrification as one of the key forces behind the movement known in Europe as "rationalization" of industry, entailing "closer control over the pace and continuity of effort by the labor force."[20] This latter formulation resonates with the observations of David and Wright concerning the confluence during the 1920s of technological developments and the diffusion of new managerial practices.

What does this remarkable parallelism imply for our thinking about general purpose technologies? First, it is encouraging confirmation that factory electrification was indeed a GPT, with pervasive effects across virtually all manufacturing industries. Because central-source power generation required large fixed-capital investments, which in turn opened opportunities for capital-saving conversions across a wide range of industries, we should expect to see many common features in the experience, even in countries that differed in many other respects. Secondly, however, once underway, the diffusion of electricity as a primary power source in manufacturing establishments seems

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[19] *Ibid.,* p. 385.

to have proceeded more rapidly in the UK than in the US during the post-World War I era. The electricity supply industry Britain had started down a very different and more decentralized course during the period 1880 to 1914, and the development of large central generating plants serving regional networks was a comparatively late phenomenon, initially confined to the Northeast.[21] The Central Electricity Board was established by Parliament only in 1926, but progress thereafter was rapid, with the bulk of the national power grid being constructed between 1929 and 1933.[22]

Consistent with this lag behind the US in the widespread availability of cheap purchased electric power for its industrial districts, in Britain the growth of TFP in manufacturing was slower during the 1924 to 1929 interval than it was over the course of the following cyclically comparable period, 1929 to 1937.[23] Furthermore, it appears that by the end of the 1930s the extent of diffusion of electric power in British manufacturing as a whole essentially matched that in the US.[24] We interpret this rapid catchup as an aspect of the experience of a "follower" country, which can adopt a well-developed technology from abroad relatively quickly, without having to retrace all the

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[20] Feinstein, Temin and Toniolo, *European Economy,* p. 80.

[21] See Hughes, *Networks of Power*, for comparisons between Britain, Germany and the US, which highlights the early lead of the latter in developing extensive regional universal electrical supply networks based upon 3-phase A.C. current, particularly in the Midwest. On the continuing entry during 1900-13 of many small DC-based electrical supply companies in Britain — to which the North East regional network built by Mertz was the exception — see Hannah, *Electricity*, esp. p. 38.

[22] Feinstein, Temin and Toniolo, *European Economy,* p. 181.

[23] Matthews, Feinstein and Odling-Smee, *British Economic Growth*, p. 610.

[24] *Ibid.,* p. 385, note 5.

steps and mis-steps of the social learning trajectory that had occurred in the country that pioneered the application of the technology in question.

Thus a second point brought out by this comparative approach to the subject is that the pace of GPT diffusion may be very different in leader and follower nations, a consideration that GPT theorists have thus far largely overlooked. This observation, of course, can be read as lying squarely within the tradition of historical analysis springing from Thorstein Veblen's remarks on "the penalties of taking the lead," and made familiar in the literature of development economics by Alexander Gerschenkron's more elaborate formulation of "the advantages of economic backwardness."

Ryoshin Minami's account of factory electrification, *The Power Revolution in the Industrialization of Japan*, offers us another case in point. Electricity was employed as motive power in the Japanese cotton spinning industry at least as early as 1903, and the first industrial use of purchased electricity followed within a few years as the development of electric utilities reduced the cost of purchased power. The timing and sequencing of subsequent developments closely matched those in the US: from the end of World War I up to the mid-1920s the group drive system continued to be used in electrified spinning factories, with unit drive being introduced in those departments where the machinery required variations in speed. Beginning in the 1920s, however, increased domestic production of small 6-8 hp induction motors (so-called "ring motors") facilitated the more general diffusion of unit drive throughout the industry.

While both contemporaries and later analysts in Japan agree in identifying the same range of advantages associated with the transition to the unit drive system as those observed in US factories, the available direct quantitative evidence on the magnitude of the impacts upon productivity in Japan is quite limited. Minami cites a study based upon

1938 data, which found that the switch to unit from group drive in the production of 20-count yarn raised output per spindle while reducing power consumption by 7-8 percent.[25] But, the greater profitability of weaving factories in Japan that were employing electric motors to drive their power-looms, in comparison with those using steam engines, or petroleum powered engines, is firmly documented by Minami's net profit rate estimates for 1910 and 1926 (see "Power Revolution", pp.252-252). Electrification in this era yielded essentially the same higher rate of return in small as in large factories, whereas the high fixed costs of steam power made it far less suited for use by the country's many small-scale weaving establishments. Consequently, Minami's discussion of the weaving industry concludes:

> In small plants, the introduction of electric motors made mechanization possible; it promoted the transition from hand looms to power looms, which raised production efficiency and improved cost performance. In large plants, the transition from non-electric engines to electric motors decreased production costs and improved output quality.

A similar observation can be made regarding the role played by small electric motors in the mechanization of Japan's match industry during the 1920s. This was a "modern" (which is to say a Western, non-traditional) branch manufacturing that had

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[25] Moriya, *Boskei Seisanhi Bunseki*, p. 80. is the source discussed by Minami ("Power Revolution,: p. 213-214). In the same place, Minami takes note also of a 1923 study of Japanese spinning mills that were using steam-generated electric power, in which it was found that the costs of installing the equipment needed for the unit drive system were 10 to 27 percent above that required for the group drive. This, of course, does not consider the capital-savings in building a new plant designed for the unit-drive system.

been established as an export activity during the closing quarter of the nineteenth century – based on the availability of low-wage labor. The formation of the Swedish Match Trust in 1921 soon led to a crisis, as Japanese matches were driven out of foreign markets and two large-match-making companies were founded with the intention of dominating the home market. That outcome, however, failed to eventuate, because the mass of small-scale factories were able to survive by introducing match-making machines (of German design) which could profitably be powered by small electric motors.

In comparison with the US, and *a fortiori* with Britain, Japan's "age of steam power" was "historically compressed" by the rapid process of factory electrification. Thus, although the timing was coincident with, and the order of diffusion by industry closely resembled that of the United States, Minami points out that by 1930 the transition to the new power regime actually was more complete in Japan even though – or perhaps because – it had been "entirely dependent on borrowed technology."[26] Thus, the impact of factory electrification on productivity was augmented in the case of Japan by the special circumstance that this transition already was underway before the mechanization of manufacturing plants had been completed, and it was through the introduction of small electric motors and the unit-drive that the modernization and mechanization of small-scale industry was accomplished.

In view of this history, a close parallelism between the time path of productivity growth experienced by the Japanese manufacturing sector as a whole and that observed for the US during the opening third of the twentieth century is what one might well have anticipated would be observed. That expectation is reassuringly fulfilled: over the

[26] Minami, "Power Revolution', pp. 9, 138-141.

period 1908-1938, according to Minami's estimates, the average total factor productivity growth rate was about 2.9 percent per annum, whereas in the US the corresponding growth rate for the 1909-1937 interval was slightly slower, averaging 2.5 percent per annum.[27] The acceleration in TFP growth up to the peak in the 1920s is present in both cases, although the productivity growth surge in Japanese manufacturing was far less discontinous. The rates there averaged 2.2 percent per annum in the period 1908-1920, 4.3 percent per annum during 1920-1930, followed by a decline back to the 2.2 percent level during 1930-1938. By contrast, the variations of the average TFP growth rates in US manufacturing (corresponding to the series in Figure 1) were more pronounced: they show a rise from the negligible level of 0.2 percent per annum during 1909-1919 to 5.3 percent per annum during 1919-1929, and then drop back to slightly under the 2 percent per annum mark in the period 1929-1937. Viewed against the benchmark provided by the Japanese experience, the US pattern suggests that effects of World War I on industrial investment may well have delayed the diffusion of the unit-drive system and

[27] The trend TFP growth rates presented by Okhawa and Rosovsky, *Japanese Economic Growth,* Table 4-2, are similar to those in Minami, *Power Revolution*, Table 1-3, over the period as a whole, averaging 3.3 percent per annum during the 1912-1938 interval. But they display a quite different temporal pattern, suggesting that manufacturing productivity growth in the 1920s was *slower* than that during the surrounding years. Clearly, the Okhawa-Rosovsky estimates do not correlate well with the course of Japanese factory electrification that has been described here. But neither do they square with the more recent estimates provided by Minami's work, which depend upon different underlying data. The latter departs from the procedures of Okhawa and Rosovsky in making adjustments for changes in hours of work and capital utilization, as well as in making use of more appropriate factor income share estimates as weights for the input growth rates.

attendant factory reorganizations, thereby creating a potential for more rapid "catch-up" that was exploited during the next decade.

On the other hand, it does not follow that the process of "catch-up" in the aftermath of developments that delay the diffusion of a new GPT will automatically translate into higher average rates of growth in labor productivity and TFP. In Britain, even during the "surge" period 1924-1937, the average pace of growth in manufacturing TFP remained (at 1.9 percent per annum) far under both the Japanese and the US rates recorded during the 1920s.[28] A proximate explanation for the larger, American-British "gap" may be found in the faster pace of increases in average manhour productivity that had become established in US manufacturing following World War I. This suggestion directs our notice to another, underlying aspect of difference between the experiences of these two industrial economies.

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[28] The TFP calculations for US manufacturing without allowance for purchased energy inputs perhaps are those most directly comparable with the estimates for Britain from Matthews, Feinstein and Odling-Smee ("British Economic Growth"), which were cited in the text above. That US rate for the long period from 1889 to 1909 averages 0.7 percentage points, and corresponds closely to the 0.6 percent per annum pre-1914 trend rate in Britain. The same productivity growth measures for the US shows a rise to 5.3 percent per annum during 1919-1929. See David, "Computer and Dynamo": Table 2, Cols. 4,7, for these TFP estimates, which already have been cited in connection with the US-Japanese comparison. Note that whereas the acceleration to the 1920s peak in these rates involved a jump of 4.7 percentage points, the weighted average of the multifactor productivity growth rates (adjusted for purchase energy inputs) in US manufacturing industries indicate a still greater acceleration, involving a jump of 5.1 percentage points.

Where the US and British records in this era diverged most sharply was in regard to the labor market. An upward jump in the real hourly wage between 1913 and 1924 was in fact common to both countries, and indeed to many other countries at that time, being occasioned in a proximate sense by global economic developments in the form of the inflation during the years 1915-1920 and the subsequent sharp deflation of 1920-1921.[29] About the same (4.5 percent per annum) average rate of increase in real unit labor costs was experienced by the manufacturing sectors of both countries over this 1913-1924 interval, even though the rise of the real wage rate in Britain was accentuated by the one-time national reduction in hours of work, enacted in 1919, a development that had no counterpart in the US prior to the 1930s.[30] But, as has been noted, the rise in real unit labor costs in the US was followed closely by a spectacular (5 percentage point)

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[29] According to Matthews, Feinstein and Odling-Smee, *British Economic Growth*, Table 6.5, the domestic (UK) aconomy-wide rise in real unit labor costs between 1913 and 1924 averaged 3.2 percentage points per annum when calculated on a manhour basis, but only 1.3 percentage points per annum on a manyear basis. This difference reflects the shortening of the work year in Britain, which, however, was not a factor in the US experience during the same period.

[30] The average annual rates of increase in manufacturing money wages inflated by the wholesale price index are found to be 4.5 percent and 4.4 percent, for Britain and the US, respectively. The underlying industrial money wage rate and price series for Britain are drawn from Mitchell (*International Historical Statistics of Europe*), Tables B4 and H1; the corresponding US data are those described in David and Wright ("Early Twentieth Century Productivity Growth"), Figure L1 and the accompanying text discussion (p 20).

jump in the annual growth rate of TFP, whereas Britain's TFP acceleration was far less pronounced in both absolute and relative terms.[31]

Undoubtedly there were many factors contributing to the observed contrast in the proportionate relationship between the movement of real wage rates and the productivity of labor in the two countries; thus, there are no compelling reasons to expect the quantitative impact of the diffusion of the same capital-embodied GPT to be identical across economies, just because its qualitative effects were similar. Because US manufacturing firms had long experience with adapting to high-wage conditions, it is quite plausible to suppose that they were more readily able to accelerate the restructuring of labor relations that was already underway in many industries. An additional country-specific feature of the American economy that also may account for the differentially stronger US response to the altered state of the labor market might be found in the better match between the technologies advanced by electrification and the country's institutions of education and worker training.

On this latter point, recent research by Claudia Goldin and Lawrence Katz suggests that the new manufacturing technologies of this era were, indeed, well adapted to the attributes of the high school graduates emerging from educational reforms in the US in the decades just prior to the 1920s. Our examination of the data they have developed, and other, related evidence, indicates that this was not because the American secondary school systems of the day were supplying industry with a workforce whose members had received specific cognitive information and particular skills required by

[31] During the decade of the 1920s, the US increased its already large labor productivity lead vis-à-vis Britain, and also Germany. See Stephen Broadberry, "Manufacturing and the Convergence Hypothesis."

the new, electrified manufacturing technologies. Rather, the new factory regime increasingly called for workers who were literate and numerate enough to be readily "instructable" on the shop and factory floor; employers in the technologically more sophisticated industries sought workers who could accustom themselves to a succession of work routines, and who would be reliable in the execution of mechanically assisted tasks where consistency of performance had become more important in the context of integrated, high-throughput systems of production. High school attendance and high school completion appear to have constituted signals of these attributes and of the motivation to respond to experience-based wages and job promotion incentives that were designed to stabilize and upgrade the quality of the workforce employed by the leading manufacturing firms in this era.[32]

In contrast, the same decade has been identified as one of missed opportunity for the British educational system, as the older apprenticeship institutions were in decline, yet were not replaced by new forms of technical and continuation schooling.[33] Thus, a third broad implication of these cross-country comparisons is that the impact of any particular GPT diffusion may be strongly conditioned by circumstances affecting the supply of complementary productive inputs. To the extent that GPTs have a capability for widespread applications across many branches of the economy concurrently, if they successfully percolate and are able to take hold in that fashion, they will most likely give rise to synergetic interactions and positive feedbacks. The availability of

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[32] See Goldin and Katz, "Origins of Technology-Skill Complementarity"; David and Wright, "Early Twentieth Century Growth Dynamics," section 4.

[33] M. Sanderson, "Education and Economic Decline;" Stephen Broadberry and Karin Wagner, "Human Capital and Productivity."

correspondingly generic complementary inputs therefore is likely to constitute a critical constraint, not only upon the extent of the GPTs diffusion, but upon the impact this has upon productivity growth. The historical case at hand suggests that critical factors in differential productivity performance may have been the management competencies rooted in the prior industrial experience, and policies affecting access to "educational attainment signals of general worker quality (as distinguished from traditional craft apprenticeship) sought by employers in establishment that were becoming committed to factory electrification.[34]

Dynamos and Computers: Uses of History and Historical Analogy

By drawing an explicit analogy between the dynamo and the computer, David's essay of that title sought to use the US historical experience to give a measure of concreteness to the general observation that an extended phase of transition may be required to fully accommodate and hence elaborate a technological and organizational regime built around a general purpose digital computing engine. This regime transition

[34] In "The Rise of Intangible Investment," Abramovitz and David discuss some aspects of the reciprocal historical relationships between the emergence of educational-attainment based hiring standards in US labor markets and the formation of perceptions of material advantage associated with extended schooling, and the growth of popular support for the movement towards public provision of mass secondary education -- even at the appreciable costs to many families of foregoing earnings from their children's labor. This dynamic process is one in which there are positive feedback externalities of the kind found more generally at work in market-driven, *de facto* "standards-setting for network industries." See David, "Economics of Standardization in the Information Age", for further discussion of the latter subject.

hypothesis” has suggested itself as a possible resolution of the so-called “productivity paradox,” wherein new computer and information technologies (now commonly designated as ICT) have been rapidly and visibly diffusing through the economy at the same time that the growth rate of TFP has fallen to historic lows, in the US particularly. An understanding of the way in which the transmission of power in the form of electricity came to revolutionize industrial production processes tells us that far more was involved than the simple substitution of a new form of productive input for an older alternative. In both the past and current regime transitions, the pace of the transformation may be seen to be governed by the ease or difficulty of altering many other technologically and organizationally related features of the production systems involved.

Recent estimates of the growth of computer stocks and the flow of services therefrom are consistent with the view that when the “productivity paradox” began to attract attention, the US economy could be said to have still been in the early phase of the deployment of ICT. Figures developed by Dale Jorgenson and Kevin Stiroh reveal that in 1979, when computers had not yet evolved so far beyond their limited role in information processing machinery, computer equipment and the larger category of office, accounting and computing machinery (OCAM) were providing only 0.56 percent and 1.5 percent, respectively, of the total flow of real services from the (non-residential) producer durable equipment stock. But these measures rose at 4.9 percent in 1985, and had ballooned to 13.8 percent by 1990, and 18.4 percent two years after that.[35] Thus, the extent of “computerization” that had been achieved in the whole economy by the late 1980s was roughly comparable with the degree to which the American manufacturing sector had become electrified at the beginning of the twentieth century. When the

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[35] Jorgenson and Stiroh, “Computer Investment, Capital and Productivity,” pp. 3-4.

historical comparison is narrowed more appropriately to the diffusion of secondary motors, a proxy for the spread of the unit drive, the growth rate for 1899 to 1914 is almost precisely the same as that for the ratio of computer equipment services to all producers' durable equipment services in the US.[36]

Although there seems to be considerable heuristic value in this historical analogy, a cautious, even skeptical attitude is warranted regarding the predictions for the future that some commentators have sought to extract from the quantitative resemblance between the two transition experiences. For one thing, statistical coincidences in economic performance are more likely than not to be mere matters of coincidence, rather than indications that the underlying causal mechanisms are really one and the same. One may use the historical evidence quite legitimately when suggesting that it is still too early to be disappointed that the computer revolution has not unleashed a sustained surge of readily discernible productivity growth throughout the economy. But that is not the same thing as predicting that the continuing relative growth of computerized equipment must eventually cause a surge of productivity growth to materialize, nor does it say anything whatsoever about the future pace of the digital computer's diffusion. Least of all does it tell us that the detailed shape of the diffusion path that lies ahead will mirror the curve traced out by the electric dynamo during the early decades of the twentieth century. One cannot simply infer the detailed future shape of the diffusion path in the

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[36] David, "Digital Technology's Evolution," provides this and other quantitative indicators, including comparisons of the decline in the real price of computer services with that of purchased electricity, that dispose of criticisms brought against the dynamo analogy's relevance, based on the argument that the much greater rapidity of innovation in the computer revolution renders the two cases incomparable.

case of the ICT revolution from the experience of previous analogous episodes, because the very nature of the underlying process renders that path contingent upon events flowing from private actions and public policy decisions, as well as upon the expectations that are thereby engendered — all of which still lie before us in time.

Eschewing blind faith in historical repetition, we nonetheless can draw insights from the record of analogous past experiences that help us to understand the so-called "productivity paradox" by indicating relevant margins and constraints governing the linkage between new information technologies and the rise of measured productivity. Here there is a case to be made for viewing the path taken up the present as one among a number of available alternatives -- a path whose selection, viewed in retrospect, was responsive to considerations that led away from a tight coupling between new technological artifacts and the task productivity of the individuals and work groups to whom those tools were offered.[37]

The widespread diffusion of the stored program digital computer is intimately related to the popularization of the personal computer as a "general purpose" technology for information processing and the incremental transformation of this "information appliance" into the dominant technology of information processing. For the personal computer, as for its parent the mainframe, and its cousin the minicomputer, adaptation and specialization has been required to apply a general purpose information processing machine to *particular* purposes or tasks. It is something of an historical irony that the

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[37] The following draws upon David ("Understanding Digital Technology's Evolution," Section 4), and the more detailed treatment by David and Steinmueller ("Understanding the Puzzles and Payoffs of the IT Revolution," Section 7) of the productivity implications of the general purpose formulation computer technology that has characterized the personal computer revolution,

core elements of the adaptation problems attending this GPT's diffusion into widespread business application may be seen to derive from a trajectory of innovation that emphasized the "general purpose" character of the paradigmatic hardware and software components.

During the 1970s it was recognized that a general purpose integrated circuit, the microprocessor, afforded the flexible means of solving the problems of electronic system designers who found themselves confronted by an ever growing array of application demands. At the same time, efforts to down-scale mainframe computers to allow their use for specialized control and computation applications supported the birth of the minicomputer industry. These two developments provided the key trajectories for the birth of the personal computer. As microprocessors became cheaper and more sophisticated, and applications for dedicated information processing continued to expand, a variety of task-specific computers came into existence.

One of the largest markets for such task specific computers created during the 1970s was that for dedicated word-processing systems, which appeared as an incremental step in office automation, aimed at the task of producing documents repetitive in content or format such as contracts, purchase orders, legal briefs, and insurance forms, that could be quickly modified and customized based upon stored formats and texts. They became attractive and were often adopted where the production of forms and texts generated full time work for more than a single employee. But the inability of the vendors of the pioneer dedicated word-processing hardware to furnish their customers with new software -- for they had adopted a strategy of providing only proprietary software -- led to both a perceived and actual absence of flexibility; the technology was not responsive to the proliferating user needs arising from the growing number of product installations.

The displacement of dedicated word processors by personal computers thus came relatively rapidly in the mid-1980s, driven by the apparent superiority of the latter in a number of the relevant dimensions of comparison. The personal computer was quickly perceived to be more "flexible" and more likely to be "upgrade-able" as new generations of software were offered. Moreover, personal computers could use many of the same peripherals, such as printers: because the widespread adoption of the new technology raised the demand for compatible printers, the dedicated word processors found themselves unprotected by any persisting special advantages in printing technology.

The dedicated word processor's demise was re-enacted in numerous markets where dedicated "task-specific" data processing systems had begun to develop.[38] The elimination of task-based computing in favor of general purpose computers and or multi-purpose software packages was in a sense the main thrust of the "PC revolution" that was completed in the course of the 1980s.[39] The "general purpose" software

[38] See the discussion in Steinmueller, "The US Software Industry."

[39] In the medium and large enterprises of 1990, what remained was a deep chasm between the "mission critical" application embedded in mainframe computers and the growing proliferation of personal computers. The primary bridge between these application environments was the widespread use of the IBM 3270, the DEC VT-100 and other standards for "intelligent" data display terminals, the basis for interactive data display and entry to mainframe and minicomputer systems. From their introduction, personal computer had software enabling the emulation of these terminals, providing further justification for their adoption.

produced for the emerging standard platforms (IBM PC and Apple Macintosh) not only discouraged task-specific software, it also created a new collection of tasks and outputs specifically driven by the new capabilities such as "desk top publishing," "presentation graphics," and "advanced word processing." All of these changes improved the "look and feel" of information communication, its quality and style, the capability for an individual to express ideas, and the quantity of such communications. But, singly and severally, they made very little progress in changing the structure of work organization or the collective productivity of the work groups employing these techniques.

The early trajectory of the personal computer's evolution thus may be seen as having cut across the development of an entire family of technically-feasible information processing systems focused on the improvement of "task-productivity" in applications ranging from word processing to manufacturing operations control. In many cases, it also precluded effective development of collective "work group" processes whose synergies would support multifactor productivity improvement. Instead of "breaking free" from the mainframe, these general purpose engines often wound up "slaved" to the mainframe, using a small fraction of their capabilities to emulate the operations of their less expensive (and less intelligent) cousins, the "intelligent" display terminals. The information systems departments of large organizations soon faced a growing array of demands for access to databases and reporting systems, so that managers might construct reports more to their liking, using their new spreadsheet tools.

Although the "personal computing" revolutionaries had kept their promise that the new hardware would soon match the computing performance of the mainframes of yesteryear, what they had not achieved, and could not achieve by this technological leap was a radical, rapid reconstruction of the information processing activities of the organizations to which the equipment and software was being sold. Rather than contributing to the rethinking of organizational routines, the spread of partially networked personal computers supported the development of new database and data entry tasks, new analytical and reporting tasks, and new demands for "user support" to make the general purpose technology deliver its potential.

This is not to claim that the process should be regarded as socially sub-optimal, or mistaken from a private business perspective. A clear basis for such judgements, one way or the other, presently exists. It appears that what was easiest in an organizational sense tended to be the most attractive thing to undertake first. The local activities within the organization that were identified as candidates for personal computer applications often could and did improve the flexibility and variety of services offered by the company internally and externally to customers who, through the intermediation of personnel with appropriate information system access, would receive an array of service quality improvements. Arguably, many of these quality improvements contributing to the problems of productivity measurement, because they fail to be captured in the real output statistics of the services sector, even though they might enhance the revenue generating capacity of the firms in which they are deployed. The availability of 24-hour telephone reservation desks for airlines, or the construction of worldwide networks for securing hotel, rental automobile, or entertainment reservations, represent welfare improvements for the customer. But these do not appear in the measured real GDP originating in those sectors, nor in the real value of expenditures on final goods and services. Of course, the same point may be, and has been, made about the tendency of service quality improvements -- including safety improvements connected with the switch from gas lamps to electric lighting, and the replacement of horse-drawn trams by electric railways -- to slip through the national income and product statisticians' net.[40]

Historical Reflections on "General Purposeness" and the Future of the ICT Revolution

The historical trajectory of computer technology development now appears poised to take a portentous change of direction. At least three new dimensions are emerging strongly enough in commercial applications to deserve brief notice. None of these developments are likely to displace the use of personal computers in the production and distribution of information that must be highly customized, or that arises from the *ad hoc* inquiries similar to the research processes for which the general purpose computer was originally invented. What they do promise is greater and more systematic efforts to integrate information collection, distribution and processing efforts. In attempting to take advantage of these opportunities, enterprises and other institutions are forced to re-examine workflow and develop new methods for information system design.

First, a growing range of information technologies have become available that are purpose-built and task-specific. Devices such as supermarket scanners were applied to a wide range of inventory and item tracking tasks and related "data logging" devices were to be found in the hands of maintenance, restaurant, and factory workers. The environmental niches in which these devices were able to achieve a foothold are ones where the mass produced personal computer was neither appropriate nor robust. These more "task specialized" devices have become sufficiently ubiquitous to provide the infrastructure for task-oriented data acquisition and display systems, in which up to date

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[40] See, e.g., David, "Computer and Dynamo," Nordhaus, "History of Lighting."

and precise overviews of the material flows through manufacturing and service delivery processes.

Secondly, the capabilities of advanced personal computers as "network servers" has become sufficiently well developed that it is possible for companies to eliminate the chasm between the personal computer and mainframe environment by developing the intermediate solution of client-server data processing systems. This development is still very much in progress and reflects the more complete utilization of the local area networks devised for information and resource sharing during the personal computer era. In this new networked environment, the re-configuration of work organization becomes a central issue, strategic and practical issues surrounding the ownership and maintenance of critical company data resources must be resolves, and these often are compelling enough to force re-design of the organizational structure.

Thirdly, the development of Internet technology has opened the door to an entirely new class of organization-wide data processing applications as well as enormously enhanced the potential for collective and cooperative forms of work organization. Applications and their maintenance can be controlled by the technical support team who would previously have been responsible for the company's centralized data resources. The common standards defining Internet technology have the fortuitous feature that virtually all personal computers can be similarly configured, facilitating not only intra-company network but also *inter*-company networking.

The "general purpose" trajectory followed by the spectacular development of personal computer technology has greatly reduced the price-performance ratio of the hardware, without effecting commensurate savings in the resource costs of carrying out many specific, computerized tasks. Some part of the limited resource savings clearly has been transitional, as personal computers were added to existing mainframe capacity, rather than substituted for it, and, indeed, were under-utilized by being allocated the role of intelligent terminals. This aspect of the story bears some striking similarities with the early progress of factory electrification, wherein the use of the group drive system supplemented without replacing the distribution of power within factors by means of shafts and belting; this added capital to an already highly-capital-using industrial power technology, without instigating any reorganization of factory layout and routines for materials handling. It was not, however, until the dynamo could be effectively integrated into individual tools under the unit drive system that the major capital-saving contributions to multi-factor productivity growth from thorough-going factory redesign could be realized.

A similar structural change seems likely to emerge, based on the development and diffusion of digital information appliances -- robust and specialized tools that are embedded in hand-held devices, carried on belts, sown into garments, or worn as head-gear -- and linked through sophisticated networks to produce complex and interactive systems.[41] This may indeed be a promising trajectory of ICT development that will impinge directly upon specific (and hence more readily measurable) task performance.

Other portents for the future may be seen in the expansion of inter-organizational computing for the mass of transactions involving purchase ordering, invoicing, shipment tracking, and payments, all of which continue at present to absorb much specialist white-collar labor time. Such service occupations might be viewed as the modern-day counterparts of the ubiquitous materials-handling tasks in the manufacturing sector that

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[41] See, for example, the vision presented recently by Norman in "The Invisible Computer," esp. Ch. 11.

became the target of mechanization innovations during the 1920s. A continuation of the presently still-limited growth of "tele-working" in the US, where only about one-fifth of the workforce time in large service sector firms is now provided via data communications networks with employees' homes – eventually would yield significant capital-savings in the reduced requirement for commercial office space and transport infrastructure facilities.

Major physical and organizational reconfigurations of this kind, which lend themselves to application across a wide array of specific branches of the economy, as was the case in the dynamo revolution of the early twentieth century, would seem to hold out the most promising prospects for the early twenty-first century to see the potentialities of the information technology revolution realized in a sustained, "yeast-like" surge of productivity growth.

References

Abramovitz, M. and P.A. David. " The Rise of Intangible Investment: the US Economy's Growth Path in the Twentieth Century," in D. Foray and B.-A. Lundvall, eds., *Employment and Growth in the Knowledge-Based Economy*, (OECD Documents). Paris: OECD, 1996.

Bresnahan, T., and M. Trajtenberg. "General Purpose Technologies: Engines of Growth," *Journal of Econometrics* 65 (1995): 83-108.

Broadberry, S. "Manufacturing and the Convergence Hypothesis," Journal of Economic History 53(1993): 772-95.

Broadberry, S., and K. Wagner. Human Capital and Productivity in Manufacturing during the Twentieth Century," in *Quantitative Aspects of Post-War European Economic Growth*, edited by B. van Ark and N.F.R. Crafts. Cambridge: Cambridge University Press, 1996.

David, P.A. "Some New Standards for the Economics of Standardization in the Information Age," Ch. 8 in *Economic Policy and Technological Performance*, eds., P. Dasgupta and P. Stoneman, Cambridge: Cambridge University Press, 1987.

David, P.A. "Computer and Dynamo: The Modern Productivity Paradox in a Not-too-distant Mirror," in *Technology and Productivity*. Paris: OECD, 1991.

David, P. A. "Understanding Digital Technology's Evolution and the Path of Measured Productivity Growth: Present and Future in the Mirror of the Past." A paper for the White House Conference on the Digital Economy, Washington, D.C., May 25-26, 1999. (Revised and forthcoming in *Understanding the Digital Economy*, eds., B. Kahin and E. Brynolfsson, MIT Press.

David, P. A. and W. E. Steinmueller. "Understanding the Puzzles and Payoffs of the IT Revolution: The 'Productivity Paradox' after Ten Years.” Ch. 1 of *Productivity and the Information Technology Revolution*, edited by P. A. David and W. E. Steinmueller, Harwood Academic Publishers, forthcoming in 2000.

David, P.A., and G. Wright. “Early Twentieth Century Growth Dynamics: An Inquiry into the Economic History of ‘Our Ignorance’.” Stanford: SIEPR, Discussion Paper No. 98-3, 1999.

Devine, W. Jr. “From Shafts to Wires,” *Journal of Economic History* 43 (1983): 347-72.

Devine, W. Jr. “Electrified Mechanical Drive: The Historical Power Distribution Revolution,” in S. Schurr et al., *Electricity in the American Economy*, New York: Greenwood Press, 1990.

DuBoff, R. *Electric Power in American Manufacturing 1889-1958*. New York: Arno, 1979.

Feinstein, C.H. *Domestic Capital Formation in the United Kingdom 1920-1938*. Cambridge, England: Cambridge University Press, 1965.

Feinstein, C.H., Peter Temin and Gianni Toniolo. *The European Economy Between the Wars*. Oxford: Oxford University Press, 1997.

Gerschenkron, A. *Economic Backwardness in Historical Perspective*. Cambridge, Mass: Harvard University Press, 1969.

Goldin, C., and L. Katz. “The Origins of Technology-Skill Complementarity,” *Quarterly Journal of Economics* 113 (1998): 693-732.

Gordon, Robert J. “US Economic Growth Since 1870: One Big Wave*?” American Economic Review* 89 (May 1999): 123-128.

Harberger, A.. “A Vision of the Growth Process,” *American Economic Review* 88 (1998): 1-32.

Helpman, E., editor. *General Purpose Technologies and Economic Growth.* Cambridge, MA: The MIT Press, 1998.

Hannah, L. (1979). *Electricity Before Nationalisation*. London: Macmillan, 1979.

Hounshell, D. *From the American System to Mass Production*. Baltimore: JHU Press, 1984.

Hughes, T.P. *Networks of Power: Electrification in Western Society, 1880-1930*. Baltimore: JHU Press, 1983.

Jerome, H. *Mechanization in Industry*. New York: National Bureau of Economic Research, 1934.

Jorgenson, D., and K. Stiroh. "Computer Investment, Capital and Productivity in the US," *Economics of Innovation and New Technology*, 4 (1995).

Kendrick, J. *Productivity Trends in the United States*. Princeton: Princeton University Press, 1961.

Matthews, R.C.O., C.H. Feinstein, and J.C. Odling-Smee. *British Economic Growth 1856-1873*. Stanford, CA: Stanford University Press, 1982.

Minami, R. *Power Revolution in the Industrialization of Japan, 1885-1940*. Tokyo: Kinokuniya Co, 1987.

Mitchell, B.R. *International Historical Statistics of Europe, 1750-1988*, Third Edition, Basingstoke, England: MacMillan, 1992.

Moriya, Fumio, *Boskei Seisanhi Bunseki*, Kokyo: Nippon Hyoronsha, 1948, p. 80.

Nordhaus, William D. “Do Real Output and Real Wage Measures Capture Reality? The History of Lighting Suggests Not,” Ch. 1 in *The Economics of New Goods*, T.F.

Bresnahan and R.J. Gordon, eds., Chicago: The University of Chicago Press for the NBER, 1997.

Norman, Donald A. *The Invisible Computer: Why Good Products Can Fail, the Personal Computer is So Complex, and Information Appliances are the Solution*, Cambridge, MA: MIT Press, 1998.

Okhawa, Kazushi, and Henry Rosovsky. *Japanese Economic Growth: Trend Acceleration in the Twentieth Century*, Stanford, C.A.: Stanford University Press, 1973, Table 4-2.

Sanderson, M. "Education and Economic Decline, 1890s-1980s," *Oxford Review of Economic Policy* 4 (1988): 38-50. Reprinted with postscript in C.H. Feinstein, ed., *The Economic Development of the United Kingdom since 1870*. Cheltenham, UK: Edward Elgar.

Schurr, S.H., et al. *Electricity in the American Economy*. New York: Greenwood Press, 1990.

Steinmueller, W. E. (1996). "The US Software Industry: An Analysis and Interpretative History," in D.C. Mowery, ed., *The International Computer Software Industry*. Oxford: Oxford University Press, 1996: pp. 15-52.

Veblen, T. *Imperial Germany and the Industrial Revolution*. New York: MacMillan, 1915.